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have strongly affected nucleosynthesis in particular. The expansion time in a charge-dominated cosmology is proportional to $(1 + Z)^{-3}$ (cf. eq. [A19]; Z = redshift) in the early history of the universe; the expansion time is proportional to $(1 + Z)^{-2}$ in a standard radiation-dominated universe. Hence the universe may spend much less time at a given Z in the charge-dominated picture than in standard cosmologies. This effect is important for element production, as will be discussed below. In principle, the electrons (say) that produce the net charge surplus might also influence nucleosynthesis by direct interaction with other particles. However, an electron surplus large enough to be cosmologically significant, even at present, would probably represent a negligible fraction of the mass (but *not* energy) in the universe; the number of surplus electrons would be tiny in comparison with the number of electrons whose charge is balanced by protons and nuclei. The ratio of surplus to "ordinary" electrons could not have been larger in the past (because charge must be conserved), so it is implausible that the surplus charges could have strongly modified nucleosynthesis by direct interaction with other particles.

We now consider how a charge-dominated universe may indirectly modify element production by changing the expansion time. The curve S of Figure 3 gives the expansion time as a function of Z in a "standard" big-bang cosmology that is matter-dominated for $Z \ll 10^4$, and radiation-dominated for $Z \gg 10^4$. Varying assumptions about the present matter density of the universe, Hubble's constant, etc., would change this curve slightly, but the differences would be of no importance for the present discussion. Modifications of the standard cosmology by the presence of a charged background are represented in Figure 3 by dashed lines. These lines are parametrized by

$$X = \log_{10} [\mathcal{N}^*(\text{present})/\mathcal{N}^*(\text{ref})] ,$$

where $\mathcal{N}^*(\text{ref})$ is the value of the charge density required to give a Proca energy density equal to the present mass density of the universe [clearly $\mathcal{N}^*(\text{ref})$ depends on μ]. Thus $X = 0$ represents a universe that has always been charge-dominated, $X = 5$ represents one that was charge-dominated before $Z \sim 10^4$, and $X = -10$ represents charge domination before $Z \sim 10^9$.

In the conventional big bang, nucleosynthesis is supposed to occur at $Z \sim 10^9$–10^{10} (e.g., see Peebles 1971; Schramm and Wagoner 1977; and references therein). The first step in element production is the formation of deuterium by fusion of protons and neutrons. The time scale for this process (curve D of Fig. 3) is roughly proportional to $(1 + Z)^{-3}$. Curve D is thus roughly parallel to the charge-dominated expansion-time curves of Figure 3, and the expansion time is shorter than the deuterium production time at all relevant Z unless $X < -8$. The cosmological production of deuterium, and hence of helium and all other heavier elements, is precluded if $\mathcal{N}^*(\text{present})/\mathcal{N}^*(\text{ref}) \gtrsim 10^{-8}$. The conventional big-bang scenario requires thermal equilibrium before $Z \sim 10^{10}$, and in particular the universe is opaque to the absorption of neutrinos by nucleons

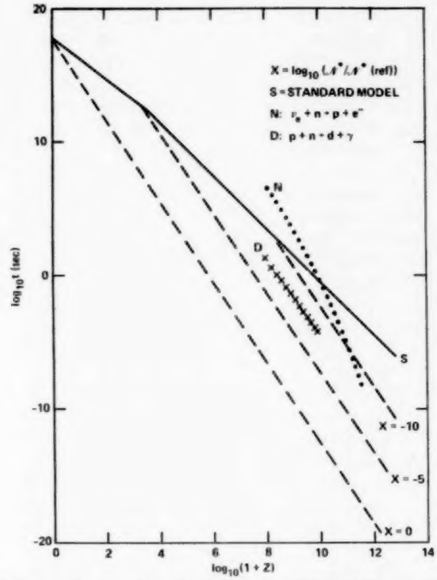

FIG. 3.—Comparison of time scales. The solid curve S gives the expansion time for a typical "standard cosmology" as a function of redshift Z; this cosmology is matter-dominated for $Z \ll 10^4$ and radiation-dominated for $Z \gg 10^4$. The dashed lines represent the modification of this cosmology by nonzero background charge; these lines are parametrized by $\log_{10} [\mathcal{N}^*(\text{present})/\mathcal{N}^*(\text{ref})]$, where $\mathcal{N}^*(\text{ref})$ is the charge density required to give a present Proca energy density equal to the matter energy density [clearly $\mathcal{N}^*(\text{ref})$ depends on μ]. The curve D gives the time scale for deuterium production by the process $p + n \rightarrow d + \gamma$, and curve N gives the time scale for the neutrino absorption process $\nu_e + n \rightarrow p + e^-$.

at this epoch. Curve N of Figure 3 represents an approximate calculation of the time scale for the process $\nu_e + n \rightarrow p + e^-$ (the time scale for the analogous $\bar{\nu}$, p absorption is comparable). For equilibrium at $Z = 10^{10}$, X must be smaller than -12. Hence for nucleosynthesis to proceed as in the normal big-bang scenario, $\mathcal{N}^*(\text{present})$ must be smaller than $10^{-12}\mathcal{N}^*(\text{ref})$. For

$$10^{-12} \ll \mathcal{N}^*(\text{present})/\mathcal{N}^*(\text{ref}) \ll 10^{-8} ,$$

nucleosynthesis would proceed in some way that would have to be determined by detailed calculations. For $\mathcal{N}^*(\text{present})/\mathcal{N}^*(\text{ref}) \gg 10^{-8}$, nucleosynthesis would not take place at all.

If one accepts the arguments favoring cosmological nucleosynthesis (reviewed by Schramm and Wagoner 1977), one must conclude that $\mathcal{N}^*(\text{present}) \ll 10^{-8}\mathcal{N}^*(\text{ref})$ and that the universe could not have been charge-dominated for Z much smaller than 10^9. It would then follow that the charged background has no bearing on the present-day expansion of the universe; moreover, if $\mathcal{N}^*(\text{present}) \ll 10^{-12}\mathcal{N}^*(\text{ref})$, the charged background would have been unimportant, even at the epoch of nucleosynthesis.

Another constraint on models of this type follows from the thermal character of the 3 K background radiation (J. Barrow, private communication). It is widely thought that Compton scattering of photons on electrons before the epoch of recombination is the mechanism that brought matter and radiation into thermal equilibrium. Since the Compton scattering cross section is less than or equal to the Thomson cross section σ_T at all energies (Heitler 1954), matter and radiation could never have reached equilibrium unless at some epoch the expansion time had been much larger than $(n\sigma_T c)^{-1} \propto (1 + Z)^{-3}$. But in the charge-dominated cosmology the expansion time itself scales as $(1 + Z)^{-3}$; and since the required inequality is not satisfied at the present epoch, a universe that is charge-dominated at present would have expanded too rapidly for thermalization ever to have occurred. An elementary calculation shows that thermalization requires that the universe was not charge-dominated after $Z \sim 10$–300, so that $\mathcal{N}_*(\text{pres})/\mathcal{N}_*(\text{ref}) \lesssim 10^{-4}$ to 10^{-1}. Although this constraint is much less stringent than those derived from considerations of nucleosynthesis, its empirical foundations are firmer.

Even if the universe were charge-dominated only before the epoch of nucleosynthesis, the charge density could still have exerted a major influence on the evolution of the universe. During the charge-dominated epoch the dominant energy density of the universe is characterized by a pressure = energy density equation of state. Such an equation of state has been suggested as solving some of the difficulties related to inhomogeneities and entropy production in the early universe (Zel'dovich 1972; Barrow and Matzner 1977; Barrow 1977, 1978). If the universe were charge-dominated before, say, $Z = 10^{12}$, the $p = \mathscr{E}$ condition would have obtained, but the expansion would not have been charge-dominated at $Z = 10^{10}$ and nucleosynthesis would proceed as in the conventional picture.

IV. SUMMARY

The novel cosmology discussed above is based on Proca's generalization of electrodynamics, for which the inverse Compton wavelength μ of the photon is nonzero. Because $\mu \neq 0$ is not consistent with gauge invariance, Proca's electrodynamics is aesthetically defective in the eyes of many theoretical physicists. However, the only certain statements about the value of μ that can be made must be based on experiment. Currently one can be sure that $\mu \lesssim 2 \times 10^{-11}\ \text{cm}^{-1}$, and a strong case can be made that $\mu < 10^{-15}\ \text{cm}^{-1}$. Considerations based on galactic or intergalactic magnetic fields may ultimately give much smaller limits on μ.

It was shown in § II that the Proca field equations admit solutions with spatially uniform, nonzero charge density, and zero electric and magnetic fields (eq. [9]). The requirement of conventional electrodynamics that plasmas be electrically neutral, which is a consequence of the fact that the electric field in a static plasma must be small, is replaced by the requirement that the net charge density in a plasma must be spatially uniform. Direct observational constraints on the charge density of the intergalactic medium are weak. For example, no direct observations would exclude a pure-electron IGM less dense than $\sim 10^{-4}$ electrons cm^{-3} (recall that a gas of identical particles emits no dipole bremsstrahlung).

A charged intergalactic medium would, in principle, influence cosmology through the energy due to the rest mass of the particles comprising the intergalactic medium, or through the energy stored in the electrostatic potential. The latter energy, whose density $\mathscr{E} = \mu^2\phi^2/8\pi$, turns out to be dominant for charge densities large enough to have cosmological importance. It follows from the field equation (9) that $\mathscr{E} \propto (\mathcal{N}_*/\mu)^2$, where $e\mathcal{N}_*$ is the charge density. One is thus led to the remarkable conclusion that the smaller μ is, the smaller the charge density required for a given energy density becomes. This can be understood intuitively by considering that the energy required to assemble a given charge configuration increases as the range of the electrostatic force increases (see § II). As long as only upper limits on μ are known, one cannot determine whether a given value of $\mathcal{N}_*$ would produce cosmologically interesting effects. If, on the other hand, a definite nonzero value of μ were established by some experiment, observational values of, or upper limits on $\mathcal{N}_*$, could, in principle, confirm or deny significant cosmological effects of the background charge.

Since $\mu \to 0$ gives Maxwell's electrodynamics, we are confronted with a paradox. As long as we have only upper limits on μ, i.e., as long as all experiments are consistent with Maxwell's electrodynamics, no observational evidence on $\mathcal{N}_*$ can show that a charged intergalactic medium does not dominate the expansion of the universe! Only if it can be shown by experiment that $\mu \neq 0$, i.e., that Maxwell's electrodynamics breaks down at some large but finite length scale, can measurements on $\mathcal{N}_*$ determine whether a charged IGM is cosmologically important. The problem can be stated in another way: *Maxwell's electrodynamics, and indeed any theory that insists on gauge invariance, can never be shown to be valid on the scale of the universe.* If this were not so, it would in effect be possible to measure distances larger than the light horizon, or equivalently, to measure a small mass more precisely than the uncertainty principle permits (de Broglie 1954; Goldhaber and Nieto 1971).

A general-relativistic model of a homogeneous, isotropic universe with charged intergalactic medium was analyzed in § III; the cosmological constant was assumed to be zero. The cosmological model is characterized by the scale factor $R(t)$, and is completely determined by the Hubble constant H_0 and deceleration parameter q_0. These parameters are related to μ and the present background charge density by equation (21):

$$q_0 H_0^2 = \frac{2G}{3c^2}(4\pi e\mathcal{N}_{*0}/\mu)^2 .$$

In this particular cosmology the universe is closed if

$q_0 > 2$, and open otherwise. Thus, if a charged IGM dominates cosmology at the present epoch, observational limits on q_0 imply that the universe is open or just marginally closed (Gott *et al.* 1974). Observational constraints on q_0 and H_0 limit the acceptable range of $\mathcal{N}_*/\mu$; unfortunately, present upper limits on μ do not seriously constrain $\mathcal{N}_*$ (Fig. 1). For example, the conservative upper limit on μ (Davis, Goldhaber, and Nieto 1975) gives $\mathcal{N}_* < 10^{-5}\ \mathrm{cm}^{-3}$, and the plausible upper limit on μ from Crab Nebula observations (Barnes and Scargle 1975) gives $\mathcal{N}_* < 10^{-10}\ \mathrm{cm}^{-3}$. Such tiny charge densities are not likely to be ruled out by observation in the near future.

A second constraint on the cosmology comes from the age of the universe (Fig. 2). Acceptable ages are found for a wide range of q_0 if H_0 is as small as 30 km s^{-1} Mpc^{-1}. Higher values of H_0 reduce the range of q_0 compatible with the age limits, and no value of q_0 gives reasonable ages if H_0 is as high as 120 km s^{-1} Mpc^{-1}. Similar conclusions follow from age constraints applied to conventional Friedmann cosmologies (Gott *et al.* 1974).

A charged intergalactic medium could represent a net excess of, say, electrons in the universe. The number of electrons required to produce a cosmologically significant charge density is probably tiny in comparison with the number of electrons whose charge is balanced by protons. The ratio of surplus to ordinary electrons could not have been larger in the past, since charge must be conserved. It is therefore unlikely that the surplus charges could have had a major, direct effect on nucleosynthesis in the early universe. On the other hand, because charge is conserved, energy density $\mathcal{E} \propto \mathcal{N}_*^2 \propto R^{-6}$, so that if $\mathcal{N}_*$ is not identically zero, the charged background would have dominated the expansion of the universe before some early epoch (if it does not dominate now). Thus the charged background could have influenced nucleosynthesis indirectly, by dominating the time scale of expansion.

If the universe were charge-dominated at present, it would have expanded much faster in its early history than conventional cosmologies predict [$t \propto (1 + Z)^{-3}$ in a charge-dominated cosmology, $t \propto (1 + Z)^{-2}$ in a radiation-dominated cosmology]. The expansion would have been too fast for cosmological nucleosynthesis to occur, as discussed in § III. Hence if one accepts the conventional picture of element production in the early universe, one must conclude that the universe could not have been charge-dominated after $Z \sim 10^{10}$. This condition gives a constraint on the present-day charge density: it could not be much larger than about 10^{-12} of what would be needed to close the present universe. Similar arguments involving the time scale for thermalization of the 3 K background radiation require that the universe was not charge-dominated after $Z \approx 10$–300; this limit is weaker than those obtained from nucleosynthesis arguments, but does not require as great an extrapolation from observation.

Even if the charge density is smaller than the nucleosynthesis limit, but nonzero, it would have dominated the expansion at some epoch before nucleosynthesis. It has been suggested that an equation of state with pressure = energy density could solve certain difficulties that arise in reconciling observations with inhomogeneities and entropy production at early epochs (Zel'dovich 1972; Barrow and Matzner 1977; Barrow 1977, 1978). It is remarkable that a nonzero charge density automatically leads to this equation of state at some early epoch. For a suitably low present charge density the desired equation of state would hold at early epochs, but not as late as $Z = 10^{10}$, so that nucleosynthesis could go on according to the usual scenario.

A final point of interest is closely related to the fact that, given only an upper bound on μ, an observational value or limit on $\mathcal{N}_*$ does not determine whether a charged background is of cosmological significance. Strictly speaking, it can never be established that $\mu = 0$, since at any epoch t the uncertainty principle proscribes measurements of an inverse length much smaller than $(ct)^{-1}$ (de Broglie 1954; Goldhaber and Nieto 1971); in an expanding universe, the precision with which Maxwell's equations can be verified increases with time! Since μ is a constant of nature, there must have been some epoch Z_{M} such that Maxwell's equations were valid for all possible experiments [$\mu \ll (ct)^{-1}$] for all redshifts $Z > Z_{\mathrm{M}}$; certainly $Z_{\mathrm{M}} = 0$ (the present) cannot be excluded. On the other hand, the Proca energy density varies as $(1 + Z)^6$ and, unless $\mathcal{N}_*$ is strictly zero, would have been much larger than the matter and radiation energy densities for all Z greater than some Z_P. Observed values of the Hubble constant, deceleration parameter, and age of the universe are consistent with $Z_P = 0$, but a conventional cosmological nucleosynthesis scenario would require $Z_P > 10^{10}$. In any case, if $\mathcal{N}_* \neq 0$, there must have been an epoch $Z > \max(Z_{\mathrm{M}}, Z_P)$ at which (1) the expansion of the universe was dominated by the charged background, but (2) all local experiments were consistent with Maxwell's theory ($\mu = 0$)! The role of the charge background would have been vaguely analogous to that of the cosmological constant in some cosmologies, and would appear in local electrodynamics only as a constant additive term in the electrostatic potential. If for some reason the arguments for cosmological helium or deuterium production turn out to be incorrect, this paradoxical epoch could conceivably include the present.

The essence of the paradox is that, while the possibility of a charged background is a direct consequence of $\mu \neq 0$, the strongest cosmological effects of a charged background would occur when the uncertainty principle precludes measurement of μ. For example, it could be argued that it would be possible in principle to measure the background charge density and the cosmological variables H and q during the paradoxical epoch; the measured values would then imply the value of μ (eq. [21]), apparently contradicting the uncertainty principle. One might argue that the uncertainty principle, derived as it was from an essentially microscopic viewpoint, does not apply over cosmological scales; however, there seems to be no obvious justification for such a contention. A more satisfactory resolution would be to show that the

background charge density cannot be determined unambiguously unless μ can be measured independently.

The latter viewpoint is supported by the following line of reasoning. Suppose the background charge consists entirely of electrons. Suppose that, during an epoch when $(ct)^{-1} \gg \mu$, an apparatus designed to detect electrons and other familiar charged particles is employed to measure the intergalactic charge density. Under our assumptions, the instrument would measure a *number* density $\mathscr{N}_*$ of electrons and no other charged particles whatever. On the other hand, a second apparatus designed to detect electric fields would find that $E = 0$ everywhere. The experimenter could then conclude either that (1) there is a net charge imbalance with zero electric field, and that therefore Maxwell's equations are violated, or that (2) Maxwell's equations are valid but that there is an as yet undetected, positive, background charge canceling the electron charge. Further experiments aimed at confirming or denying the existence of a neutralizing positive background could be conducted. Scattering of, say, neutrons would give a null result; hence it would be concluded that the putative positive background is not subject to the strong interaction. A similar conclusion could be reached (at least in principle) for weak-interaction experiments. Scattering of charged particles would show that the positive charge could not be strongly localized, but would have to be smeared out fairly uniformly—a sort of "charged ether."

While the putative positive background might be inert to strong and weak interactions, it would have to respond to gravity. In fact, it turns out (Appendix B) that during the paradoxical epoch all gravitational experiments on the charged background would have two equally valid interpretations: (1) there is a net charge to the universe carried by ponderable matter (e.g., electrons) governed by Proca electrodynamics; or (2) the charge of the ponderable matter is canceled by a charged ether that behaves as an ideal gas whose pressure = energy density, and Maxwell's equations are valid. Only when the universe has expanded enough that μ can be measured directly can it be determined that the apparent ether does not behave like an ideal gas.

Let us return to the paradox. If the cosmological variables H and q could be determined during the paradoxical epoch, the mean energy density of the universe could be inferred. If the mean charge density of ponderable matter were measured, the *assumption* that the charge produces the cosmological energy density under Proca electrodynamics would imply a value of μ, in apparent contradiction of the uncertainty principle. However, all observations could be explained equally well by the presence of a neutralizing charged ether with the properties of an ideal gas; the cosmological energy density could be interpreted as the energy density of the ether. This second viewpoint does not involve μ at all. The second viewpoint could be repudiated only when the universe had expanded enough that direct measurement of μ was allowed by the uncertainty principle.

I wish to thank J. Barrow, D. Black, L. Caroff, R. Matzner, V. Petrosian, J. Scargle, J. Tarter, and R. Wagoner for helpful discussions on various aspects of this work.

APPENDIX A

GENERAL-RELATIVISTIC COSMOLOGY WITH CHARGED INTERGALACTIC MEDIUM

Assume that the universe is homogeneous and isotropic. In a comoving reference frame the coordinate system may be chosen so that the metric is given by the line element

$$ds^2 = c^2R^2(t)\frac{dx_i dx_i}{(1 + \frac{1}{4}kx_j x_j)^2} - c^2dt^2 \quad (i, j = 1, 2, 3) \tag{A1}$$

(e.g., Robertson and Noonan 1968); here $k = 0$ or ± 1, and $R(t)$ characterizes the scale of the universe. The metric tensor is thus

$$g_{00} = -1\,, \qquad g_{0j} = 0 \quad (j = 1, 2, 3)$$

$$g_{ij} = R^2(t)\delta_{ij}\Big/\left(1 + \frac{k}{4}x_l x_l\right)^2 \quad (i, j, l = 1, 2, 3)\,. \tag{A2}$$

A charged background medium with no electric or magnetic field yields the stress-energy tensor

$$T_{\alpha\beta} = T_{\alpha\beta}{}^{\rm EM} + T_{\alpha\beta}{}^{M}\,, \tag{A3}$$

where the part due to electromagnetic potentials (cf. eq. [14]) is

$$T_{\alpha\beta}{}^{\rm EM} = T_{\alpha\beta}{}^{P} = \frac{\mu^2}{4\pi}(A_\alpha A_\beta - \tfrac{1}{2}g_{\alpha\beta}A_\gamma A^\gamma) \tag{A4}$$

and the part due to the charged matter itself is

$$T_{\alpha\beta}{}^{M} = (p_M + \mathscr{E}_M)u_\alpha u_\beta + p_M g_{\alpha\beta}\,, \tag{A5}$$